Atacama
Large
Millimeter
Array

Summary of the First ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 January 6-13

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MEMORANDUM

To: The ALMA Community

From: Lynn D. Matthews and Geoffrey B. Crew, MIT Haystack Observatory

Date: original version 2015 February 11; updated 2015 March 29

Subject: Summary of the first ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 January 6-13

Overview

The first Commissioning and Science Verification (CSV) mission for the ALMA Phasing Project (APP) took place during the ALMA EOC Week from 2015 January 6-13. The formal commencement of APP CSV activities followed the provisional acceptance of the APP hardware during a formal review by JAO that took place on 2014 December 11.

Personnel

APP personnel on site during January CSV mission included: Geoffrey Crew and Lynn Matthews (MIT Haystack Observatory); Matias Mora (NRAO); Alejandro Saez (JAO); and Neil Nagar (University of Concepción). Additionally, Helge Rottmann (MPIfR) provided support remotely. The ALMA Science lead on site during the week was Gianni Marconi.

Objectives

The primary objectives for the first APP CSV campaign were two-fold: (1) local (i.e., short-baseline) VLBI fringe tests between ALMA and nearby sites (APEX and an ALMA antenna at the OSF); (2) systematic testing and characterization of the phasing system. A secondary goal was to begin to familiarize ALMA science and support staff with APP operations.

Resources and Set-Ups Employed

Software

APP CSV observations carried out in January used software release R2014.4. (In contrast, ALMA EOC activities during the week were being performed primarily under R10.6).

Antennas

ALMA was in a compact configuration during the mission, with maximum baselines of a few hundred meters. The APP performed observations utilizing up to 50 antennas. The array included several CM antennas that were not equipped with WVR monitors. Additionally, antenna PM01 was parked on pad TF01 at the OSF and was used by the APP Team during the week for VLBI testing.

Remote VLBI stations

Short-baseline VLBI tests were attempted using two independent remote stations. The first was PM01 at the OSF. It was operated with the two-antenna correlator TFINT, which was running a two-antenna build of R2014.4. A quartz crystal was deployed as a time standard; this crystal had previously been in use to monitor the hydrogen maser at the AOS. It was brought down in advance of the EOC week, acclimated, and installed at the OSF. (To provide a second independent time standard, a spare LORR was installed to bring down the maser reference signal from the AOS. However, this signal suffered too much 1/f noise to be usable for the LOs. It did however suffice to provide a measure of the crystal frequency drift.) The TFINT set-up was able to record a single TFB channel, providing a total bandwidth of 32 MHz.

The second remote station deployed during the mission was APEX, which formed a baseline of ∼2.1 km with the center of the ALMA array. APEX was operated in conjunction with ALMA during two 2-hour sessions on 12 and 13 January (03:00-05:00 UTC), respectively. APEX recorded in Band 6 with a bandwidth of 2.048 GHz and two digital backends—one providing a single wide channel, and the other 32 62.5-MHz channels in a single polarization (right circular). During January, the APEX team also carried out VLBI tests with the South Pole Telescope (SPT) in support of the Event Horizon Telescope project, independently of APP CSV. Because of logistical difficulties, SPT equipment and personnel were not in place in time to permit simultaneous recording during the APEX-ALMA campaigns. (SPT did manage to observe, and subsequently obtain fringes with APEX, several days after conclusion of the APP CSV mission.) Long baseline testing with SPT was beyond the scope of the January APP mission, and the lack of participation by SPT therefore did not impact the ability of APP to fulfill its objectives.

Time allocation

A total of 20 hours of ALMA array time were allocated to APP CSV during the January mission. This included hours where weather conditions were unsuitable for ALMA EOC activities. The APP also had nearly exclusive use of TFINT and the PM01 antenna during the week.

Data Collected

Observing targets for the mission were selected from the "ALMA Source Catalog" and included several bright quasars and strong spectral line sources such as Orion. Approximately 173 GB of CSV (uid) data were collected in Bands 3 and 6. VLBI-mode data were recorded simultaneously with the ALMA interferometry mode (ASDM) data, even when ALMA was not observing in conjunction with a remote station. Owing to logistical issues, the VLBI mode data did not arrive at Haystack until shortly before the second APP CSV mission in 2015 March, so a complete analysis of these data is pending. The total amount of data shipped (including all recorder testing through January) was approximately 0.2 PB. Of that, the sessions with APEX (see next section) comprised ∼28 TB.

Accomplishments

VLBI

Extensive experience was gained during the January mission in the operation of the APP's VLBI hardware and recording systems under real-life observing conditions. The APP team successfully deployed an independent VLBI station at the OSF (see above), and this set-up was initially tested in single-dish mode through observations of the CO(2-1) line (Band 6) and SiO maser lines (Band 3) toward Orion.

The APP met the objective of recording VLBI mode data simultaneously with ALMA and two nearby independent sites (antenna PM01 on pad TF01 at the OSF and APEX, respectively). However, the cadence of the data precluded the planned on-site correlation and analysis of the data.

A brief search on the PM01-ALMA baseline for a short segment of data (transferred via ftp from ALMA to Haystack) did not produce a fringe. During our testing, we experienced some issues with the pointing/focus of PM01, and the analysis suggests that for the scans recorded in Band 3 we may not have been properly pointed (Figure 1).

Significantly greater success was obtained from our local VLBI tests on the ALMA-APEX baseline—namely, the detection of a VLBI fringe on the quasar 0522-364 (Figure 2). The detection shown in Figure 2 is based on a 5-second segment of data transferred via ftp to Haystack and correlated using the Haystack correlator. A subsequent correlation of the full 5-minute scan shows an appropriate scaling of signal-to-noise ratio with increased integration time.

Because ALMA and APEX used completely independent time standards (hydrogen masers), as well as independent electronics and backends, this was a true VLBI experiment and thus constitutes "VLBI first light" for the APP. A full analysis of the remaining ALMA-APEX VLBI data will be undertaken following the 2015 March APP CSV mission. However, a preliminary analysis shows correlation for the full duration of all scans that were successfully recorded. Furthermore, the current detection already verifies that all major hardware components of the APP are working as expected. In addition, it demonstrates the ALMA array position is known with sufficient accuracy for VLBI, that the absolute delay is understood, that the R2DBE digital backend used at APEX has acceptable correlation across the entire 1.875 GHz ALMA band, and that the APEX R2DBE can be channelized into 32 51.2-MHz bands to suitably match the spectral configuration used by ALMA.

Other Aspects of the Phasing System

In addition to the VLBI experiments, a number of tests were executed during the mission using ALMA in a standard interferometry mode in order to allow rigorous and systematic checks of the performance of the phasing system and the robustness of ASDM data products archived by the phasing system. The team has developed a CASA script to facilitate quick-look analysis of interferometry mode data. Real-time analysis of phasing data during the mission led to the following developments:

- Discovery that DownloadSumScalingData takes longer than previously owing to an update in the LTA firmware. This was fixed in the CCC.
- Confirmed that a bug persists in the autocorrelation data being archived by ALMA. This problem is independent of the APP and a JIRA ticket was created (http://ictjira.alma.cl/browse/ICT-3918).
- Identification of a sign error in the slow phasing loop correction with respect to the upper sideband. A patch was implemented, and the slow phasing corrections (as applied to individual ALMA antennas prior to summation) are now working in all four correlator quadrants, both polarizations (Figure 3).

- Fine-tuning of the performance of the fast mode phase corrections. It was found that excluding CM antennas allows significant better performance of the fast loop on the DA, DV, and PM antennas. It was also discovered that a bug fixed applied during a previous APP software mission had been reverted, negatively impacting fast loop performance. This was patched. It was confirmed that use of the fast loop improves the overall coherence of the data.

- Identification of the cause of the problem affecting the amplitude of the phased sum antenna (Figure 4). The issue was traced to an inappropriate implementation of the way various delays are applied to the data used to form the sum antenna. In brief, the front-end delays (which have values of ∼100-500 picoseconds) are optimized for baseband 1, polarization X *in Band 3*. Delay corrections for the other baseband/polarization combinations are then performed in the CDP. TelCal uses those corrected data to compute the phasing solution. However, data uncorrected for the front-end delay are being used to form the phased sum signal because the signals to sum are captured between the front end and the CDP correction.

Implications of the delay issue are also manifested in the results shown in Figure 2. The ALMA-APEX observations had been planned to take advantage of the good phasing previously observed in Band 3, baseband 1, polarization X. However, since the observations were carried out in Band 6, and the delays in that band are somewhat different (and in effect, effectively optimized *against* phasing). This means that the ALMA array was essentially performing as a single 12-meter dish. Consequently, the amplitude of the correlation in Figure 2 is a factor of $\sqrt{N_{\rm ant}} \approx 7$ lower than expected. Tests of a correction for this issue are planned for the 2015 March APP CVS mission.

Additional activities during the January mission included making contacts with members of the ALMA EOC and Array Operations teams and acquainting them with APP operations, and the presentation of an overview of the APP during the weekly science meeting at the OSF.

Continuing Activities

Following completion of the January APP CSV mission, a number of directly related follow-on activities are underway by the APP team. These include:

- Full correlation and analysis of VLBI mode data obtained in January.

- Additional reduction and analysis of interferometry mode data to characterize phasing system performance.

- Preparation of a memo detailing the problem with the application of delays to the phase sum and outlining possible fixes to improve the performance. An initial fix is being tested during the 2015 March mission.

- Modification of TelCal code to enable operating observing mode with multiple spectral channels per TFB, providing more options for TFB phase estimates.

- R2014.6 verification, in coordination with ADC.

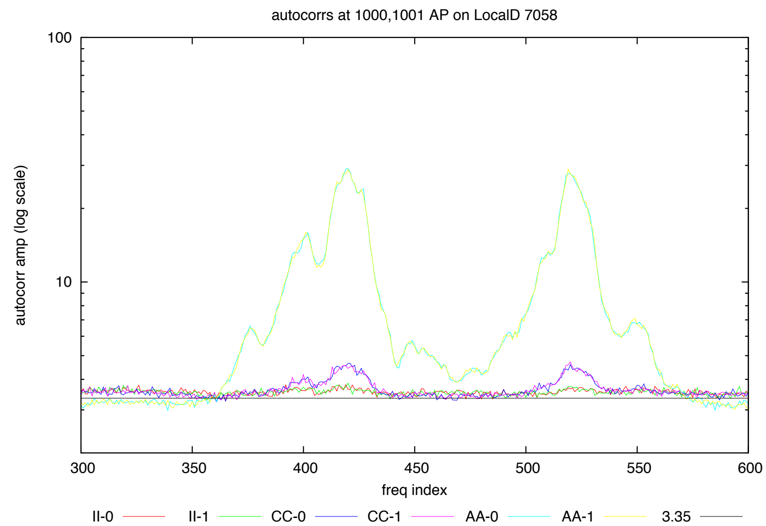

Figure 1: Autocorrelations of Orion SiO v=1, J=2-1 maser (Band 3) lines captured at an intermediate stage of the VLBI processing. For the VLBI analysis, the equivalent of 50 ms dump times were used and the autocorrelations of these are plotted after phase-up. The horizontal axis is proportional to frequency in the sub-band; the vertical axis (log-scale) is the relative amplitude with frequency. The phased array lines (AA-0 and AA-1) show considerable structure. The lines recorded from the comparison antenna (CC-0 and CC-1) show prominently above the noise floor. The lines for the OSF antenna (PM01, labelled II-0 and II-1) are barely distinguishable from the noise floor, possibly because of pointing errors.

- Coordination with ALMA EOC on the scheduling of future APP CSV activities.
- Conversion of our test observing scripts to observing scripts that utilize the SSR.

Additional information on the 2015 January APP CSV mission is available on the mission wiki page:

https://ictwiki.alma.cl/twiki/bin/view/AppMissionChileCommissioning01

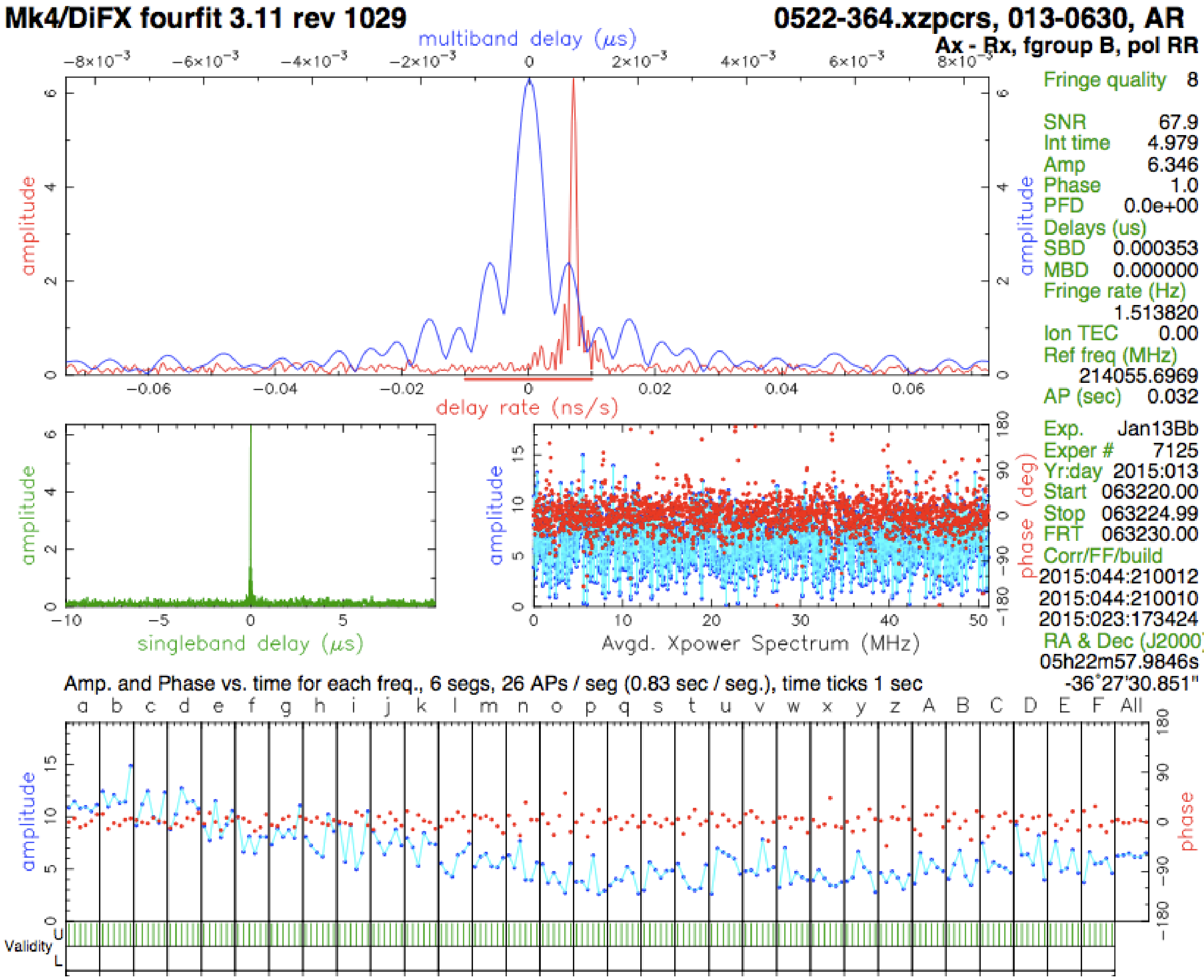

Figure 2: VLBI fringe detection on the quasar 0522-364, obtained on a 2.1 km baseline between ALMA and the APEX antenna on 2015 January 13. Five seconds of data are shown. The high signal-to-noise ratio of the detection (∼68) is evident from the clear peaks in the delay rate (red curve, top panel) and in both the single-band delay (green curve, center-left panel) and multi-band delay (blue curve, top panel). The center-right panel shows amplitude (blue) and phase (red), averaged over all baseband channels at a resolution of 100 kHz. (The VLBI correlation was performed at 3.125 kHz resolution). The lower plot shows amplitude (blue) and phase (red) as a function of time for each of the 32 51-MHz frequency channels. (The wings of the 62.5 MHz ALMA TFB channels were not included). The decrease in amplitude across the band is largely due to the characteristics of the APEX digital backend, which has better response at low frequencies. As described in the text, owing to an issue with the application of delays, the ALMA array was effectively *unphased* during this session, hence the correlated amplitude is as expected for a single 12-m dish.

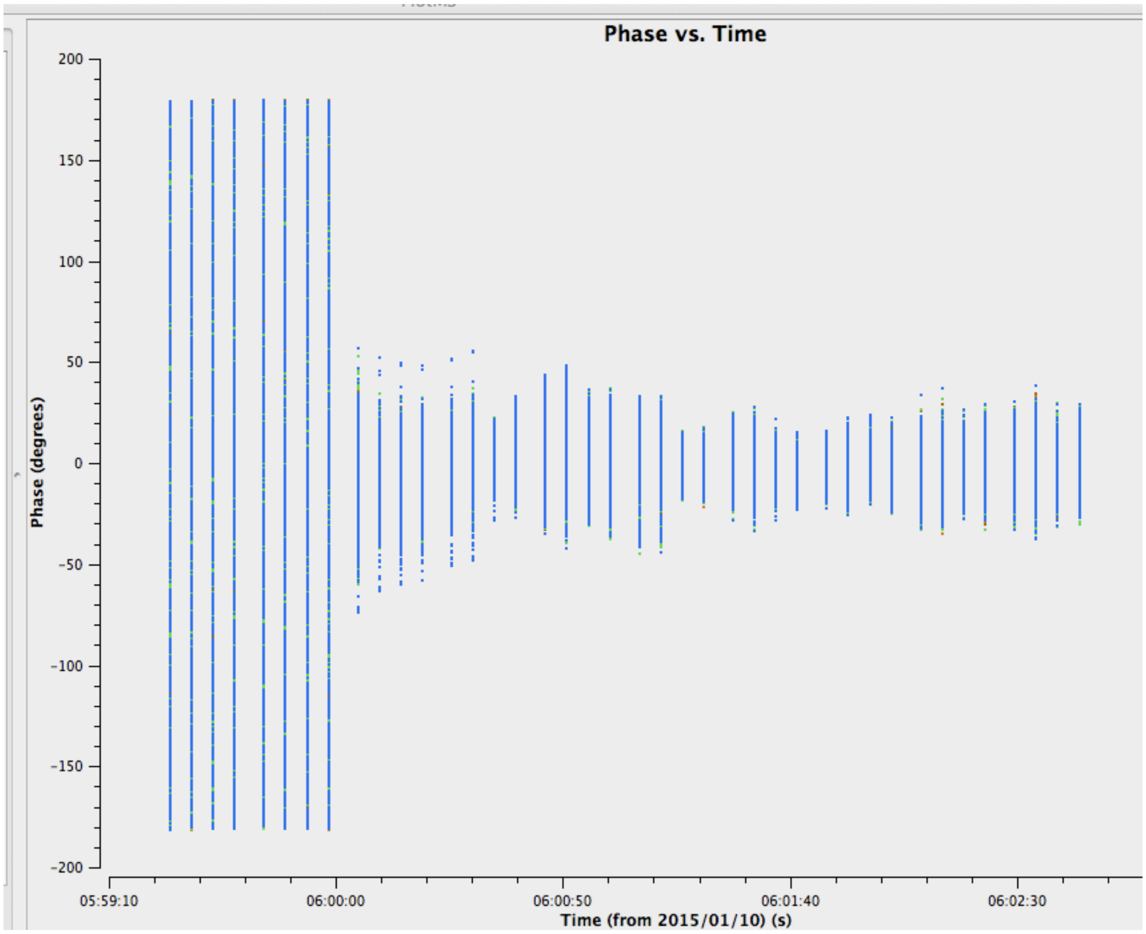

Figure 3: Phases as a function of time during a 3.5-minute Band 3 observation of the quasar 0730-116 with the ALMA phasing system on 2015 January 9. The baselines for 41 antennas that received phasing corrections are plotted (polarization XX). Each of the four correlator quadrants is shown in a different color (although the symbols overlap). Phase-up (i.e., the expected convergence of the phases toward zero for an unresolved source) is clearly observed in all four quadrants.

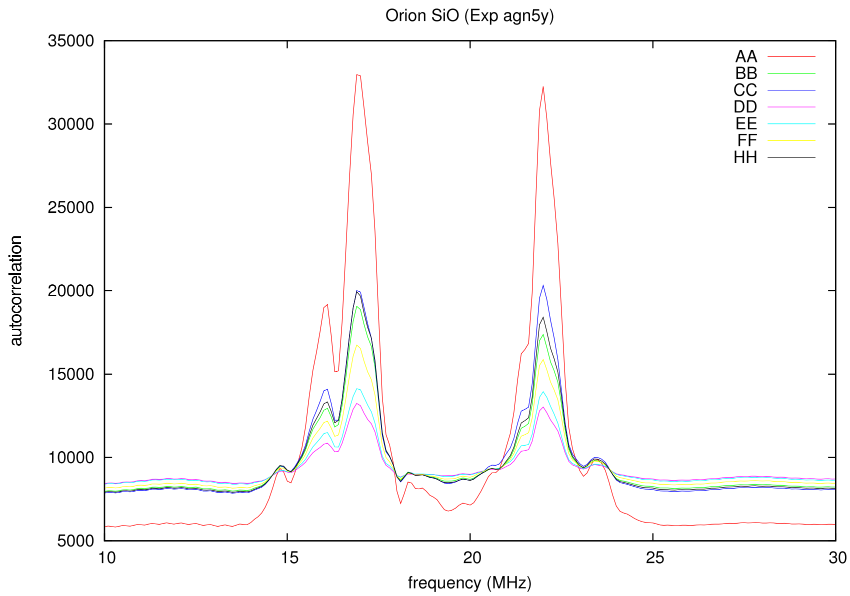

Figure 4: Spectra of the Orion SiO v=1, J=2-1 maser (Band 3) obtained with the ALMA phasing system and recorded on the APP's Mark 6 VLBI recorders on 2015 January 11. The spectra are the autocorrelations of the phased sum, which comprised the sum of 44 ALMA antennas. The different colors indicate different correlator quadrant/polarization combinations (AA= quadrant 1, polarization XX; BB= quadrant 1, polarization YY, etc). GG is absent. Flux density is in arbitrary units. The highest intensity is measured in quadrant 1, polarization XX. All other quadrants/polarizations show noticeable attenuation. This has been traced to a problem in the way delays are being applied to the data used to form the sum.